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Effect of Head-Slaved Visual Image Roll on Spatial Situation Awareness

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We examined whether the inclusion of a third *head-slaved* "roll" degree of freedom (dof)—in addition to pitch and yaw dofs—to control the orientation of a remotely-viewed or computer-synthesized scene can enhance spatial situation awareness. Six subjects were required to match the position and orientation of stationary target markers on a remote taskboard by manually placing response markers on an identical local taskboard. Subjects could only view the remote taskboard through images transmitted to a head mounted display (HMD) from a motorized pitch-yaw-roll camera platform; they could see neither the local taskboard nor their own limbs. Results show that, while systematic overshoot errors in azimuth judgment occurred regardless of the roll condition, the addition of the roll dof to the platform had no statistically discernible effect on the subjects' ability to match the position (*i.e.*, azimuth and elevation) of the remote targets. Absence of the roll dof, however, did affect the subjects' judgment of target orientation when their heads were at maximum elevation (pitch) and azimuth (yaw) combinations.

INTRODUCTION

A small number of novel motorized camera platforms developed for remote viewing tasks have incorporated a "roll" degree of freedom (dof) in addition to the pan (azimuth/yaw) and tilt (elevation/pitch) kinematics that point the cameras of most conventional systems (Comeau and Bryan, 1961; Bolas and Fisher, 1990; Tachi, Arai, Maeda, Oyama, Tsunemoto, and Inoue, 1991; and Jacobsen, Iversen, Davis, Potter, and McLain, 1991). The inclusion of the roll dof is intended to allow the platform to mimic the full pitch-yaw-roll orientation capability of the human head. Roll in these platforms, however, does not affect the ability to position and aim the cameras.

By slaving the roll of the camera platform to the human operator's head, the scene available in a head mounted display (HMD) will always appear correctly oriented with respect to the stationary operator's body referenced sense of the horizontal. It has been proposed that control of the roll dof in either remotely viewed or computer synthesized scenes may benefit task perception and performance (Bolas and Fisher, 1990)—*i.e.*, improve situation awareness. The addition of a third roll kinematic dof, however, complicates camera platform mechanical design and controller implementation, and can contribute to degraded equipment performance because of system complexity and to higher monetary cost because of an increased component count.

In this paper, we examine whether a head-slaved roll dof in a motorized camera platform affects one aspect of human situation awareness: the ability to judge the *planar* position and orientation of remote objects as seen through the cameras on a head mounted display (HMD). Since the remote vision task to be studied does not require depth perception, cues that arise from roll induced (or other) motion parallax are not a factor.

METHODS

Apparatus

The experimental apparatus, shown in Figure 1, is divided into a remote station containing the camera platform and a local station at which the human operator/subject is seated. Both stations consist of identical "semicircular" cylindrical (0.6 m radius, 225° circumference, 1.2 m tall) foam core taskboards. The camera platform base is located such that its yaw axis is coincident with the remote cylinder's long axis and its cameras are aimed at the cylinder's inner surface. The subjects were similarly positioned during the experiments: facing the inside of the taskboard, with the task board's base at mid-thorax height.

The camera platform used in the experiment (Molly™, Fake Space Labs, Menlo Park, CA) supports two parallel-mounted (75 mm separation between optical axes) miniature monochrome CCD cameras. (Bolas and Fisher, 1990) The platform has pan (yaw), tilt (pitch), and roll axes that are independently driven by computer controlled servo motors under orientation commands from an electromagnetic spatial sensor (Space Navigator, Ascension Technology Corp., Burlington VT) affixed to the HMD (VPL EyePhone, VPL Inc., Palo Alto, CA) worn by the subject. The HMD contains two LCD color screens which receive images transmitted by the corresponding left and right cameras. However, since the cameras are monochrome, the displays were rendered in black and white. While wearing the HMD, the subjects can see neither the local taskboard nor their own limbs. The remote taskboard could only be viewed by the subjects through the HMD.

Also visible in Figure 1 are rectangular target markers that can be suspended magnetically at any arbitrary position and orientation on the inner surface of the remote taskboard. Adhesive-backed rectangular *response* tags were applied manually on the inner surface of the local taskboard by the subjects to match perceived target marker positions and orientations.

Pre-experiment

At the start of each experiment, the subjects' head yaw axis was aligned approximately with the center of the cylinder curvature by positioning the chair on which they were seated. The subjects remained seated in this position throughout the pre-experiment set up and actual experiment periods.

The set up period was used to establish a center "reference" target position as well as the range of fixed target marker positions to be used throughout the experiment. The reference position was determined by having the subject look straight ahead into the HMD, parallel to his internally perceived horizontal plane, and then directing the experimenter to position a target marker on the remote taskboard at the center of a circular reticle that was inserted in the right camera lens system and appeared fixed with respect to the right eye's LCD.

Subjects were instructed, both for the set up and actual experiment period, to use the reticle to align their gaze at the remote object of interest. The reticle served three purposes: 1) it forced each subject to be right eye dominant when performing the task; 2) it required that the subject always look through the same region of the lens system; and 3) it ensured that the subject visually acquires the target through the center of the HMD and camera lenses, where optical distortions are at a minimum. Since the reticle was symmetric, it provided no orientation cues to the subject.

After the reference marker was placed, the subject was asked to yaw his head, without moving his torso, to a maximum azimuth position on his left side and pitch upward to the highest attainable elevation and then guide the experimenter to position a new marker on the taskboard at the center of the reticle. This process was repeated for maximum elevation at maximum azimuth on the right side and again for maximum elevation at the center azimuth. A second set of target markers was placed at approximately the same three azimuths but at a downward pitch (elevation). All target positions were checked and adjusted to ensure that the subject could touch the local taskboard with his hand at the locations which he judged to correspond to the target positions on the remote board. The targets were oriented arbitrarily and uniquely for each subject at "non-canonical" rotations (*i.e.*, not at 0°, 30°, 45°, 60°, 90°, *etc.*). Once the set up procedure was completed, the seven targets remained in place for the entire experiment.

These extreme azimuth-elevation combinations were selected for the target locations because experiments with more modest (and comfortable) ranges of head pitch and yaw did not reveal any effect related to camera platform roll on position and orientation judgments made by one preliminary subject. It was expected that any effect would become more pronounced as involuntary concomitant head roll grew as a consequence of greater pitch-yaw combinations.

Experiment

The independent variable of primary interest in the experiment was the presence/absence of head-slaved roll in the camera platform. When platform roll was enabled, the platform would follow the full three orientation (yaw-pitch-roll) dofs of the subject's head. When roll was disabled, the platform could only yaw and pitch—roll was fixed at zero (*i.e.*, both camera lens axes were always in a plane perpendicular to the pitch axis).

At the beginning of the actual experiment, the subject was instructed first to visually locate specific target markers on the remote taskboard by moving only his head, and then, by using a special rectangular dispenser similar in shape to the target markers, to hand-place response tags on the local taskboard at the perceived position and orientation of the remote targets. The subject was handed the special dispenser containing a single numbered response tag as the particular target to be acquired was called out by the experimenter. After placing the response marker on the local task board, the subject was provided with a new numbered tag, and the next target was identified. The seven targets were grouped in a block and always called out in the same sequence. The order of target selection was determined so that consecutive markers on the remote taskboard could not be seen in the HMD at the same time.

After each block of seven targets was acquired, the camera platform roll condition was toggled and the block of seven targets were repeated in order. Half the subjects began with roll enabled; half with it disabled. A total of seven repetitions of the seven target cycle were conducted for each roll condition. This resulted in a total of 98 target acquisitions per subject, with the entire experiment being completed during one 45 minute sitting.

Data Processing

Target and response marker positions and orientations were measured with respect to an orthogonal yellow grid that permanently covered both task boards. Because of red filters on the camera lenses, the grid was not visible to the subjects. The scale and protractor used for the measurement provided accuracies of no worse than 0.03 inches for position and 0.5° for orientation.

Rectilinear measurements from the surface of the cylinders were referenced to the subject's "straight ahead" position by subtracting the coordinates of the center marker on the remote taskboard from all target and response values. The measurements were then converted into spherical azimuths and elevations. Raw position response errors were calculated by subtracting response from target azimuths and elevation. Raw orientation errors were derived by subtracting response from target marker orientations as measured directly on the two taskboards. Raw azimuth, elevation, and orientation errors were conditioned further to remove any systematic bias (*e.g.*, initial offsets in the camera platform, offsets in subject seating, misalignments of the spatial sensor with respect to the HMD, and misalignments of the HMD's LCDs relative to the subject's head) by subtracting the average error from each block of seven responses. An advantage of calculating the average for each block of seven responses is that drifts in bias over the course of the experiment can be reduced.

RESULTS

Six right-handed male subjects (ages 23-47 years) participated in the full experimental protocol. Multi factor ANOVA were performed on data from the six subjects for each of the dependent variables: bias-corrected orientation, azimuth, and elevation errors—*OE*, *AE*, and *EE* respectively. The independent variables included "within-subject" factors *RC* (presence/absence of roll compensation) and *TL* (the seven discrete target locations), and "between-subject" factor *RF* (whether the roll or no-roll compensation condition series was invoked first for that particular subject). The analyses show very significant effects for *TL* on *AE* ($F = 12.033$; $df = 6,24$; $p < .001$) and *EE* ($F = 6.212$; $df = 6,24$; $p < .001$), and for combined *RC* and *TL* on *OE* ($F = 8.859$; $df = 6,24$; $p < .001$). Other combination of factors, or *RF* alone, did not affect *OE*, *AE*, or *EE* significantly ($p > .05$).

The similarity in position (*i.e.*, azimuth and elevation) response for each subject under roll and no-roll conditions is demonstrated in Figure 2. The short line segments joining the circles denote the magnitude and direction of the unbiased error with respect to the target location (unmarked end of line segments). Of interest in Figure 2 is the systematic magnifi cation in azimuth error as absolute target azimuth magnitude is increased. This effect was typical of all subjects and indicates a tendency of the subjects to overestimate target azimuth.

The difference in orientation response error between the roll and no-roll condition is depicted in Figure 3 for each subject at the seven target locations. While the magnitudes of differences in orientation errors between the two conditions are typically small, they are much more pronounced at the upper left and right corner (*UL* and *UR*) target locations. The directions of the differences in the upper corners indicate that, when camera platform roll was disabled, the subjects' responses were more counterclockwise for *UL* targets and more clockwise for *UR* targets. Since we assume that the roll-enabled platform provides the more complete orientation information, these differences are attributed to misjudgments when roll was disabled.

DISCUSSION

The results from these experiments show that the addition of a head-slaved roll dof to a remote camera platform does not affect the ability of subjects to judge the *azimuth* and *elevation* of stationary objects in a remote scene as viewed through a HMD. Bennett (1993) reported a similar observation over a range of azimuths in a "closed-loop" dynamic tracking task—closed-loop because the subjects could see their response cursor. The experiment described here, however, is "open-loop" because the subjects cannot see and correct their response.

The ability to judge the *orientation* of remote objects, however, is improved with the addition of platform roll for objects located at the positions that require maximum magnitude head azimuth and elevation combinations. Because of the concomitant outward head roll that occurs naturally at extreme head azimuths and elevation combinations (*i.e.*, counterclockwise for *UL* targets and clockwise for *UR* targets), the observed effect on *orientation* judgment is not unexpected, since the orientation of the remote object image will be fixed with respect to the HMD when platform roll is disabled, and thus appear to the subject to roll with his head.

The azimuth magnification effect (increase in azimuth error for large target azimuth) observed in this data indicates that the subjects overestimate their own head yaw angle when looking at the target markers. This overestimate is consistent with the undershoot reported from studies by Ellis, Smith, and Hacisalihzade (1989), and Dorighi, Grunwald, and Ellis (1993) in which subjects employed head pointing to represent judgements of exocentric orientation. Based on the direction judgment experiments of de Graaf, Sittig, and Denier van der Gon (1991), the data presented here may represent a more general tendency for overestimation of gaze direction. Furthermore, from de Graaf *et al.*'s results, one would expect this tendency to overestimate azimuth to diminish as the feedback available to the subjects on their response pointing direction is increased from our present "open-loop" case.

The implication of these results is that, except at extreme (and often uncomfortable) head azimuth-elevation combinations, the inclusion of a third roll dof to head-slaved camera platforms, moveable boom-type viewers, or computer generated simulations will not enhance the ability to judge the *planar* location and orientation of *stationary* objects in the visual scene. In many applications, one way to alleviate circumstances which would lead to these extreme head orientations (and, hence, the need for a roll dof) would be to seat the human operator in a pivoting chair so that view azimuth could be changed by yaw rotation of the whole body and elevation achieved by simply pitching the head and neck.

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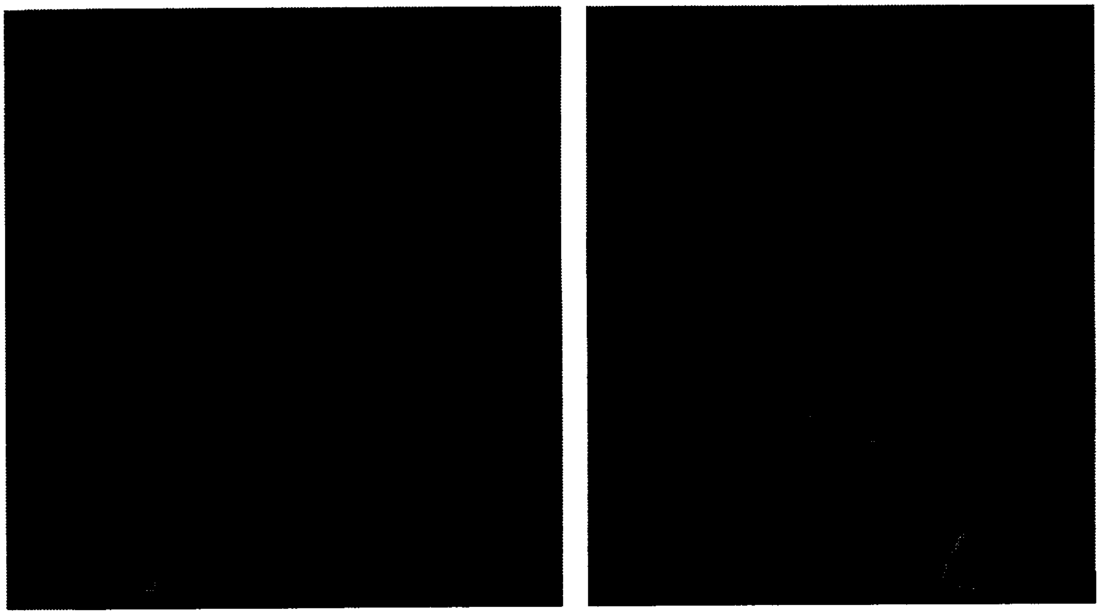

Figure 1. (Left) Remote station with three dof camera platform. (Right) Local station with subject wearing HMD. The subject is placing a tag in response to upper left target.

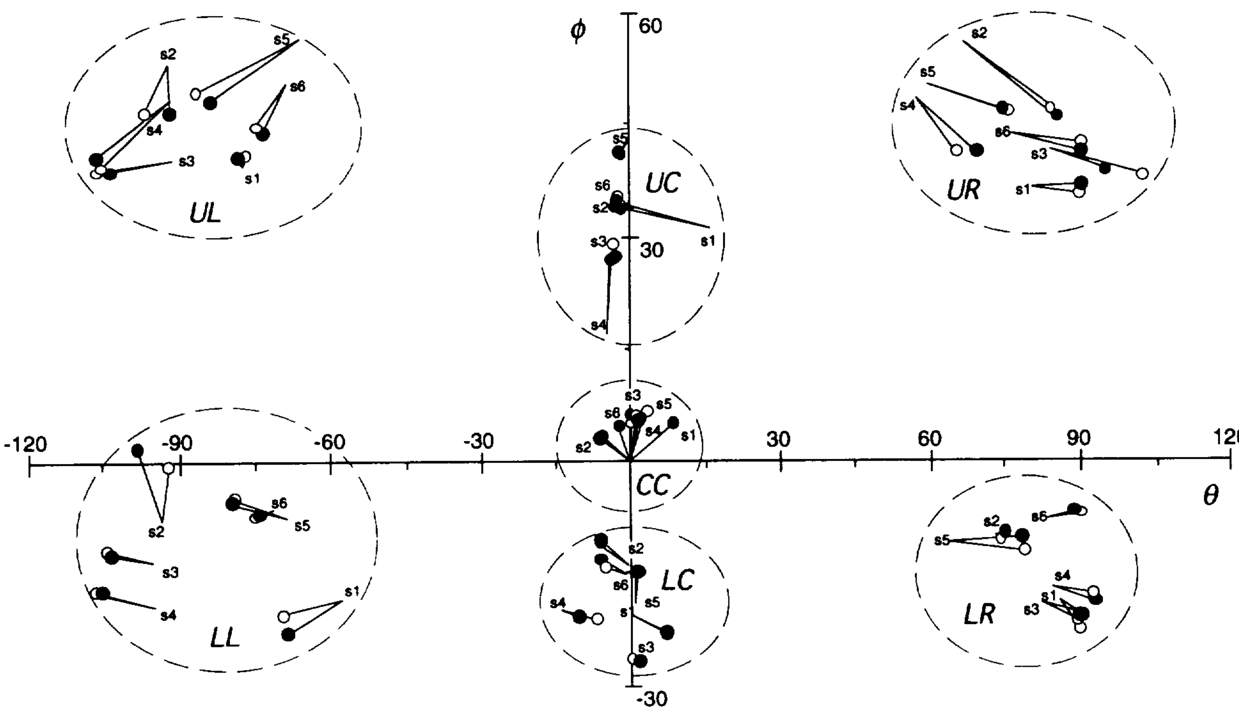

Figure 2. Target and average unbiased response for all six subjects (*s1*,..., *s6*). θ and ϕ are the azimuth and elevation in degrees. Regions *UL*, *UC*, *UR*, *CC*, *LR*, *LC*, and *LL* denote, respectively, the upper left, upper center, upper right, center, lower left, lower center, and lower right target locations. Filled circles represent average responses with camera platform roll compensation enabled; unfilled circles the average with roll compensation disabled. The line segments join the average response (circles) for that particular subject to the corresponding target location (unmarked end of each line segment).

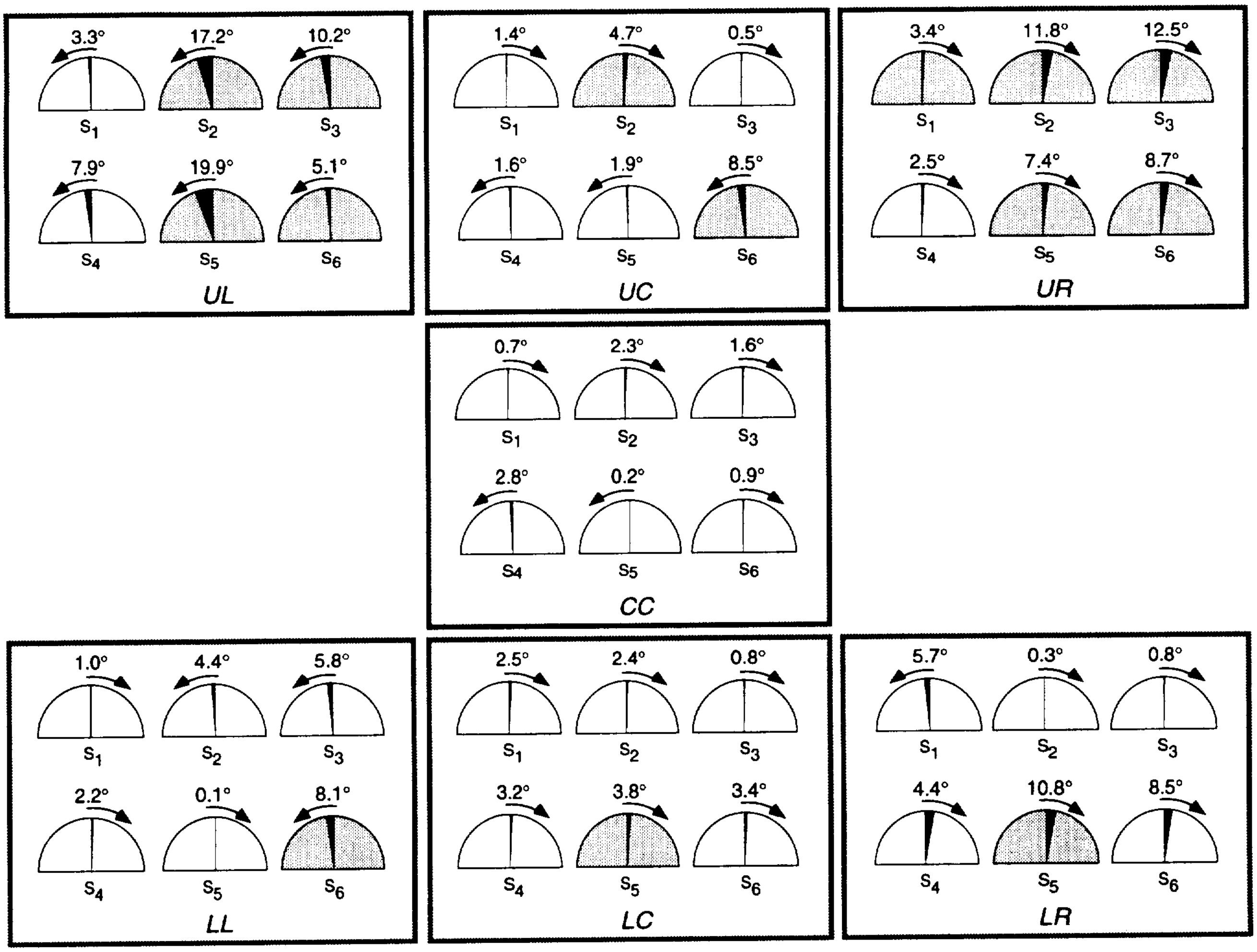

Figure 3. Difference in subject orientation response error (error when camera roll compensation is *disabled* minus error when roll compensation is *enabled*) for all six subjects at all seven target locations. *UL*, *UC*, *UR*, *CC*, *LR*, *LC*, and *LL* denote, respectively, upper left, upper center, upper right, center, lower left, lower center, and lower right targets. Solid black segments represent the magnitude of the difference out of a possible 180°; the arrows show the direction of the difference (counterclockwise is positive). Shaded semicircles indicate that the difference is significant at $p < .10$.